IGS WHITE PAPER ON LOW EARTH ORBITING GPS

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OVERVIEW.

At the upcoming IGS Governing Board meeting in Paris, Oct., 1996, the question of IGS participation in spaceborne GPS applications will be discussed. This white paper is intended to provide the Governing Board members with technical and programmatic information about GPS receiver platforms in low Earth orbit, most notably the radio occultation missions, and about their potential requirements on IGS infrastructure. It also addresses certain benefits and issues that will arise depending on the extent to which the IGS chooses to become engaged in these space-related activities.

IGS ROLE IN THE IMPLEMENTATION OF A SPACEBASED GPS NETWORK.

The IGS was extremely successful in organizing the resources of the international GPS community in the development of GPS science and applications. The pooling of resources led to an extremely efficient and rapid development of the IGS global network, the development of support centers for analysis and data archiving, and the rapid advancement of GPS science and applications. This was done because of the open nature of collaboration while maintaining friendly and supportive competition among the participants in the IGS. The development of a space network of orbiting GPS receivers could be developed as an extension of the ground network while utilizing many of the resources which the IGS currently has in place.

It is clear that the IGS ground network will be a cost effective element to most applications of space-based GPS applications. Furthermore, several participants in the IGS are also key players in the development of spacebased GPS applications. The IGS has a de facto role in the development and applications for orbiting GPS receivers and the stage is set for the IGS to play a significant role in the development of spacebased GPS receiver applications. With the development of a significant role in the arena of orbiting space receivers, the IGS will serve the broader geoscience community as well as potentially provide services for commercial interests.

The operation of a space network of GPS receivers in service to the broader geoscience community will place special requirements upon the acquisition and distribution of data from the ground network, new requirements on the analysis centers, expanded capacity for the archiving centers, or creation of new ones, and a broader representation of scientific disciplines and agencies on the IGS governing board. Therefore, the IGS will need to develop and extend its current organization.

FUTURE TRENDS FOR SPACEBORNE GPS.

These are now two space GPS receivers aboard low Earth orbiters (LEO) for scientific applications: TOPEX/Poseidon and GPS/MET. There is a very high probability that at least six additional spaceborne GPS receivers will be in orbit within the next three years: GFO (1996), ØRSTED (1997), Sunsat (1997), MIR/H-Maser(1997?), SAC-C(1998), CHAMP(1999). There are another 6-12 missions being proposed to fly before the end of the millennium that would carry one or more high performance GPS receivers. Within the next decade it is quite possible that the number of space GPS receivers will exceed the current number of IGS ground receivers!

This decade also will see greatly expanded functionality within the spaceborne GPS receiver design in connection with space operations: communications, spacecraft command and control, onboard processing of scientific data, scheduling, and so on. The missions in each successive year noted above will carry a GPS receiver with increased capability and performance. By the end of the decade the GPS receiver will no longer be considered as a flight instrument riding on a space bus. Spacecraft hardware systems and the GPS instrument will be integrated from the outset, built by a single aerospace manufacturer. Miniaturization and onboard automation will result in very low capital costs for deployment and operation of these space systems.

DEVELOPMENT OF THE SPACE ARRAY.

The space network can be developed in two ways. (1) The development of dedicated satellites carrying only a GPS receiver. Some designs involving nanoscale and microscale satellites have been proposed which are designed for optimum recovery of both occultation and gravity data. (2) The use of satellites of opportunity.

The NASA Geodynamics and Geopotential Fields program is aggressively developing the space array by providing TurboRogue GPS receivers to appropriate satellite programs. ESA plans to fly GPS/GLONASS receivers on satellites of opportunity. Other missions may also come available within the near future. Within the next decade, other agencies, commercial organizations, and independent satellite programs will develop their GPS and GLONASS programs resulting in an exponential growth of the number of orbiting GPS receivers that provide occultation data. A role for the IGS is to encourage and to provide guidance for the development of this new application of GPS technology.

GPS MEASUREMENTS FROM A LEO

Navigation and precision orbit determination (POD) of low Earth orbiters in support of altimetry and SAR missions using GPS has a very promising future. In addition to the promise of centimeter level POD accuracy, even for drag-limited LEOs, the onboard GPS receiver in conjunction with the ground global network provide a highly cost effective approach. For example, the POD function on TOPEX/Poseidon at 3 cm radial accuracy can routinely be done with a workforce of approximately 1/2 workyear/year.

In addition to their precise positioning, timing and POD functions, and expanded spacecraft operations and data processing functions mentioned above, most of these GPS receivers will probe the ionosphere using the L1 and L2 carrier phase observations (principally) and they will sound the atmosphere using the radio occultation technique to recover vertical profiles of temperature, pressure and density. In the radio occultation technique the LEO GPS receiver tracks the refracted signals from the GPS satellites as they apparently rise or set through the Earth's atmosphere. About 500 usable occultations of GPS satellites are obtained each day from a single LEO with fore and aft-looking antennas. Each occultation within the neutral atmosphere lasts about 1 minute. Ionosphere observations are more-or-less continuous and involve side-looking (and up-looking) observations as well. Given sufficient spatial and temporal sampling density, and geometric strength in the ionosphere measurements from both space and ground, continuous tomographic techniques can be used to recover electron density distributions and also ionospheric currents.

In the case of the neutral atmosphere, the radio occultation technique in its first order applications requires additional constraints in the form of assumed models for the atmosphere; e.g., it is laminar and it has spherical or ellipsoidal symmetry, and it is in hydrostatic and thermodynamic equilibrium. Refraction by the atmosphere causes a phase delay in the received GPS signal due to bending and retardation within the atmosphere. The basic observables in radio occultation technique is the Doppler profile of the carrier phase measurements and their amplitudes. The Doppler residual due to the intervening atmosphere has a direct relationship to total atmospheric refractive bending. The vertical profile of atmospheric refractivity is recovered from the temporal bending (or Doppler) profile using the assumed model symmetry and ray tracing techniques. If the local chemical composition is known, the local density follows from the refractivity at that altitude. The assumption of hydrostatic equilibrium allows one to infer the local pressure from the density profile above that site. Assuming thermodynamic equilibrium allows one to derive the temperature from the pressure and density using the gas law.

In the middle and lower tropopsphere water vapor, which has a refractivity per mole that is about 17 times that of dry air, introduces an ambiguity in deriving density from refractivity. One can invoke atmospheric models in the lower troposphere to effectively constrain dry air density thereby enabling recovery of the water vapor. Error studies and limited analyses to date with GPS/MET data using this approach are promising; good relative accuracy, particularly in the tropics appears achievable when the signal can be tracked through the lower depths of the troposphere. Because inhomogeneities in water vapor distributions create sharp vertical gradients in refractivity, the current class of GPS receivers has difficulty tracking the GPS signal through the lower troposphere. The early results from GPS/MET essentially showed a floor at an altitude of ~6 km below which only occultations through a very benign medium (e.g., winter polar regions) are possible (about 10% of the total). Recent experiments with new tracking software developed by JPL in the TurboRogue receiver on GPS/MET has been successful in reducing the altitude cutoff floor by about 50%.

GPS receivers flying in the late 1990s will enjoy an order of magnitude increase in antenna gain and they will be a lot smarter about tracking and processing signals in an adverse environment. Near real time onboard signal reconstruction and data processing with the GPS receiver are definite possibilities for the future. Uncertainty in global and regional distributions of water vapor is a major error source in short and medium-term weather forecasting. If this thrust of the GPS radio occultation technique into the lower troposphere proves technically and economically viable, the ramifications for weather forecasting may be significant.

The amplitude data from the GPS signals can be used in conjunction with the phase data to study boundary layer features and to attain sharper resolution than the Fresnel limit. The first Fresnel zone at GPS wavelengths, which is a measure of single-look resolution, is about 1 km for an LEO in a 700 km orbit.

During an occultation the vertical velocity of the point of tangency of the LEO/GPS ray path with the Earth's limb is about 3 km/s in the upper atmosphere, slowing to less than 1 km/s in the lower atmosphere because of the increasing refractivity gradient with depth. The onboard LEO receiver samples and reports the dualband carrier phase and amplitude measurements at a 50 Hz rate. Clock instabilities in the LEO GPS receiver and in the observed GPS satellite require a double differencing (or equivalent) technique to eliminate these errors. This requires that in addition to the occulted GPS satellite, the LEO GPS receiver also must track a second (or "clock") GPS satellite at the 50 Hz rate during the occultation period. Concurrently, a ground receiver must also be tracking the same two GPS satellites, except in this case, the clock error spectrum onboard the GPS satellites permits a more relaxed sample rate of 1 Hz. from the ground. All other GPS satellites observed from the LEO may be sampled at a rate driven by the ionosphere resolution requirements, for example, 1 Hz, or by data storage limits. The LEO receiver "knows" which GPS satellite is being occulted and which clock satellite to track; moreover, in choosing the clock satellite for a particular occultation it knows which ground receiver should be tracking in the high rate mode and which GPS satellites that ground receiver is tracking. In the future flight/ground coordination of tracking schedules could be maintained to minimize data volume. The current estimate for data volume is on the order of 20 Mb/day per LEO, and could go higher depending on the amount of ionosphere profiling recorded.

The co-visibility requirement for double differencing requires globally distributed ground receivers. Note that these receivers must operate at 1 Hz, and should be configured to operate with high reliability, or have suitable back-up. Six appropriately located ground stations on average enabled an ~85% recovery rate of the occultations from GPS/MET when it was operating in the occultation mode. These stations at present are at Fairbanks, Kokee Park, Tidbinbilla, Potsdam, McMurdo, and Goldstone, which are not quite ideally distributed. With a dozen stations, the recovery rate should rise to better than 99%. The geographical location of the occultation point typically is several thousand kilometers from the tracking station on the ground. For example, Potsdam allows recovery of occultations over East Asia.

Note that the data requirements for precise orbit determination of the LEO is automatically satisfied by the current, robust, globally distributed IGS network sampling at 30 sec intervals.

As a side benefit of a global network of sites operating at 1 Hz, if these sites include hydrogen masers, solutions for the GPS satellite clocks at 1 Hz can be fairly easily computed, even when the LEO is not in view. This would enable support (at least in a post-processing mode) of any ground or air-based kinematic receiver with IGS network sites.

SCIENTIFIC PRODUCTS FROM SPACEBORNE GPS RECEIVERS.

In addition to ionosphere imaging products and pressure, temperature and density profiles in the neutral atmosphere, these platforms will strengthen the POD solutions for the GPS constellation. For example, incorporating a single 10-day cycle of AS-OFF TOPEX/Poseidon GPS data into the IGS data set for that cycle reduced the formal uncertainty in the determination of the geocenter offset in the z-axis by a factor of ~3 and the equatorial components by a factor of ~2. Some of the future GPS platforms will also carry accelerometer instruments. The long-life of some of these missions, and/or their ongoing replacements, will provide valuable time variable gravity information in the low degree and order spectral coefficients.

An emerging view about the GPS radio occultation technique is that one of its principal values lies in the ability of the refractivity profiles to constrain the degrees of freedom in existing atmospheric analyses, which are based on extensive modeling and ground and space-based data programs acquisition, such as radiosondes. Independent studies performed at NCAR, MPI Hamburg and ECMWF all show that the refractivity profiles, if adequately distributed in time and space, provide a significant and important constraint that improves the accuracy of the models and enhances their predictive capability.

IGS REQUIREMENTS AND AREAS FOR DEVELOPMENT.

There are several organizational and technical elements within the IGS that should be examined if it is to operate effectively in Spaceborne GPS applications.

- IGS Governing Board.

If the IGS is to expand its purview to that of GPS space networks then the applications that concern the IGS will accordingly expand. Ionospheric and atmospheric studies as well as global real time precision navigation will become feasible areas of service. The IGS will have the option of participating in all or some of these new areas of service. With participation will come some requirements on the governing board. IGS will need to expand or modify its membership to include institutions and agencies that are active in these new areas. The IGS governing board will need to actively recruit participants on the governing board and associated working groups with the required expertise. In this regard the IGS Terms of Reference will need to be re-examined in this light and its sponsoring organizations within the IUGG should also be reviewed for comprehensiveness. The IGS governing board will also need to address the development of standards for instrumentation, data analysis, data availability, and archiving for these new applications. Moreover, the IGS will need to address the commercial aspects of these new activities especially in the areas of WAAS/GAS, atmospheric and ionospheric studies where the commercial applications are likely to become significant.

- High Performance IGS Subnet.

As discussed above, the space network will require a small subset, about 12 stations uniformly distributed within the IGS ground network, that will be capable of high data rate operations (1 sec sampling) and report the data on a near real-time basis. These stations should also be referenced to hydrogen maser clocks wherever feasible. The data from this subnet needs to be made available to the analysis centers on a subdaily and preferably continuous basis. This places requirements of high reliability upon the operation of the subnet, which probably is best achieved through redundancy either at the subnet sites themselves or through a doubling of the size of the subnetwork. The ground communication links to support these data acquisition requirements will need to be evaluated and probably upgraded in certain cases. The subnet for space array support could in essence be the IGS core network or an enhanced version of that network deployed for a more uniform global distribution. An analysis of the performance of the IGS Core network is recommended to better ascertain the upgrade requirements.

The broader IGS ground network could also provide for enhanced resolution by supplying data for tomographic analysis as well as distributed water vapor and pressure measurements. Therefore, it is important for the broader IGS network to provide its measurements in a rapid manner, perhaps on an hourly or more frequent schedule. A strong effort should also be pursued to equip the broader network with temperature and pressure sensors to improve the estimation of atmospheric water vapor.

- Data Analysis Centers.

Data from the LEO's and the high rate ground support network needs to be handled analogously to the current ground data. Existing data and analysis centers could choose to broaden their roles, and in addition, a call for new, LEO-specific centers could be made to the community. Validation of the raw data from the receiver could also be an IGS function, but in all likelihood only the center sponsoring the mission would likely perform this task. Analysis center roles are not clear; in the case of POD, gravity field and ionospheric TEC recovery, several of the present day centers can assume both the data validation and interpretation role. The requirement of an enhanced ground network for occultation places one of the requirements for WAAS, a realtime ground network, nearly at hand. The estimation of POD, clocks, and ionosphere are all requirements of Wide Area Augmented Service (WAAS) (or should we call it GAS-Global Augmented Service). The role of the analysis centers or a select small group of centers could be expanded if global real time becomes an objective. GAS is clearly an important area of commercial interest.

However, in the case of atmospheric occultation the interpretation role is involved and the current analysis centers may take on a data validation role only. The demands of these new tasks may represent more than the current analysis centers desire to supply. Therefore, it perhaps would be wise to allow for the establishment of a new class of analysis center that would perform the validation and interpretation role. The IGS should consider issuing a call for participation in the area of medium studies (i.e., atmospheric and ionospheric studies). Important players in this regard should be drawn from existing organizations engaged in atmospheric and ionospheric studies and meteorology.

- Data Archiving Centers.

A policy will also need to be developed for the archiving of these data bases. Measurement of GPS occultation data can multiply by a factor of ten the data production from an orbiting GPS receiver (20 Mbyte/day for an orbiting GPS occultation receiver vs 1

Mbyte/day for a ground receiver at 30 sec sampling). Perhaps a new data format or improved receiver technology for occultation science might result in a reduction in the size of this data set. However, the higher data rates will also be required for real time or near real-time POD efforts and possible support of WAAS/GAS. The present archiving centers should be capable of expanding capacity. However, the agency programs which currently support the archiving centers may need to expand in number since the functionality of the data sets expand beyond that of geodynamics.

- Data policy.

An extremely important aspect in the development of the space GPS array is data availability. Free and open data availability of data from the orbiting receivers and the ground support array will be necessary for a rapid advance in the applications of this new segment of the IGS network. The matter of commercial applications for these data needs to be taken into account in developing a viable policy.

- Costs

Internet data throughput: captital and recurring costs
Center expansion
Manpower/ facilities/

IN ORDER TO DEVELOP THIS BROADER ROLE THE IGS SHOULD CONSIDER:

1. Broaden the participation within the IGS and its governing board to include the atmospheric, ionospheric, and navigation agencies and institutions, with scientists, engineers, and managers.

2. Encourage the enhancement of the IGS constituent facilities including the Core network, the analysis centers and the archiving centers to provide optimum support to spacebased applications.

3. Encourage the participation of the various groups developing satellites to carry the appropriate GPS receiver hardware.

4. Encourage the development of GPS occultation science through workshops, the development of standards, data exchange formats, data policy etc.